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RESEARCH ARTICLE

On-line Locating of Generator Trips in Large Power Systems

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Abstract

Power system is a giant dynamic system. It consists of numerous generation units, transmission lines and loads. Each sudden change influences both voltage and frequency conditions. Impact intensity of such events depends on power-system operating conditions at that time and specifics of an involved power-system element. Normally the most critical event represents an unscheduled outage of a major element following a fault. It is of crucial importance for a system operator to detect and evaluate the "danger" of such events as soon as possible in order to keep the operational security of a power system at a high level by taking suitable emergency actions. One of the most important information for the operator is the location of an event origin and in case of cascaded events the corresponding time sequence of all other events that follow.

This paper describes different methods for on-line locating of generator trips in large power systems. The first and most significant step for on-line locating of generator trips is detection of it. The next step is time delay detection, observed from frequency, for which several different approaches can be used. The last step is locating of generator. In this paper two different methods are presented, the first method is multilateration and the second method is gradient search method. Their applications are demonstrated on a real case from ENTSO-E network. Results of both methods are compared.

Keywords

Disturbance detection, Multilateration, Time delay detection

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1 Introduction

This paper presents different methods for on-line locating of generator trips in large power system. Why is on-line locating of generator trip so important? The trip of an important power generator obliges the transmission grid operator to ensure energy through the balancing mechanism, because the transmission system operator interest is to provide rapidly enough energy to maintain the grid security level. After a sudden disconnection of generator, an electromechanical oscillation between the other generation units occurs. There are three different categories of power oscillations, inter-area oscillations, local oscillations and intra plant oscillations [1,2].

On-line locating of generator trips consist of several stapes. The first and most significant step is disturbance detection, but in some cases also the most difficult part of whole procedure. This is especially expressed if a small unit trips in a large power system, because the frequency drop is small and it does not effect on inter-area power oscillations in large system, with only few power measurement units (PMU) included in power system. For example, for the whole ENTSO-E network the minimum power of a tripped generator is around of 500 MW.

The next step is time delay detection. First method that can be used is cross-correlation of frequency. This method can be used in case if large generator unit trips and inter-area oscillation occurs. The second method is searching time difference between maximum deviations of approximated frequencies. This method can be used in case there are no inter-area oscillations detected or the amplitude of oscillations is not high [3,4].

The last step is estimating the location of generator trip. Two principles are presented, the gradient search method and multilateration [3,5].

The paper is organized as follows: in chapter 2 the disturbance detection is described, in section 3 the time delay detection is presented, in chapter 4 the methods for estimating of location are discussed and in chapter 5 methods are tested on the ENTSO-E network.

2 Disturbance detection

The first step in locating of generator trip is it detection. As it was previously mentioned the frequency drop and power oscillations shown in real time are indicators that point out that something is going on.

At real time the Fast Fourier Transform (FFT) can be carried out to detect amplitudes of oscillations with frequency between 0.2 Hz and 3 Hz. If the maximum amplitude of oscillations rises for more than three standard deviations from mean value and frequency drops, this is a warning of generator trip. If only oscillations are detected, the topology of the system is changed.

In our case, where data from only six PMUs are available from ENTSO-E network the oscillations with higher frequency are not always detected, due to fact that they are detected in case that PMUs are placed nearby power plant. On the other hand the outage of small generator unit in most cases does not affect the system as much as outage of the large unit and its detection is not so significant.

3 Time delay detection

When the disturbance is detected the second step in on-line locating generator trip is to detect the time delay between drops of frequency at different PMUs. First method is the cross-correlation of frequency. This method is useful if the oscillations have higher amplitude and smaller frequency.

In case if it is not so, the cross-correlation does not produce any results and method that searches time difference between maximum deviations of approximated frequencies can be applied. The frequency of 10 to 20 second is approximated with seventh order polynomial. The seventh order polynomial curve fits the best and the noise is eliminated. Then the maximums of absolute derivatives of the fitted curves are defined. The time delay is the time difference between the maximums of absolute derivatives of the fitted curves. Opposite from the cross-correlation this method does not produce any results if the oscillations have higher amplitude and smaller frequency.

4 Methods for locating of generator trips

At this point two principles for estimating the location of generator trip are presented. These two methods are the gradient search method and multilateration. For their application several different projections can be used, depending on location of power system. Their advantage is that the location of the disturbance can be located also “outside” of the area covered by PMUs. Both methods have one common disadvantage. They both propose that the velocity of electromechanical waves is constant in each direction, which is not true and in a weakly meshed system reflect this in erroneous location.

The gradient search method is based upon minimizing the distance between the purported event location and each PMU (1). This method would lead to the same solution for each case where the observation set of PMUs is the same, because the minimization of function (1) is conditioned with (2).

$$f(x,y)=\sum_{i=1}^{n_{PMU}} r_i^2 \tag{1}$$

$$r_1 \le r_2 \le \ldots \le r_{n_{PMU}} \tag{2}$$

Where x and y are the coordinates of disturbance location, n_{PMU} is the number of PMU and r_i is the distance between disturbance location and PMU.

The advantage of this method is that only sequence of detection of PMUs is important and not time delay. This advantage is also on the other hand disadvantage, because when the time oscillations are obviously seen and time delay is very accurate determinate, this does not help to improve the estimation of location of generator trip.

The second method is the triangulation/multilateration. It determines the position of disturbance using the range information estimated at several spatially separated reference points in our case PMUs. Specifically, to unambiguously localize a tag in an n-dimensional space, range information from at least n+1 reference points is required. In our case the minimal number of dimension would be four, due to fact that the x and y coordinates and velocity are unknown. But because the time of disturbance is not known the additional PMU is needed to eliminate the time between time of disturbance and time, when the frequency change at first PMU is detected. Also for these reason the placing the origin at first of the PMU is made. To estimating the location the system of N equations (3) must be solved, where x and y are eliminated from (4) and (5).

$$0=\left(\frac{2x_{n_{PMU}}}{\tau_{n_{PMU}}}-\frac{2x_1}{\tau_1}\right)x+\left(\frac{2y_{n_{PMU}}}{\tau_{n_{PMU}}}-\frac{2y_1}{\tau_1}\right)y+v^2\left(\tau_{n_{PMU}}-\tau_1\right) -\frac{x_{n_{PMU}}^2+y_{n_{PMU}}^2}{\tau_{n_{PMU}}}+\frac{x_1^2+y_1^2}{\tau_1} \tag{3}$$

$$0=v\tau_{n_{PMU}}-v\tau_1+\frac{\left(R_0^2-R_{n_{PMU}}^2\right)}{v\tau_{n_{PMU}}}-\frac{\left(R_0^2-R_1^2\right)}{v\tau_1} \tag{4}$$

$$\begin{aligned} R_0 &= \sqrt{x^2+y^2} \\ R_{n_{PMU}} &= \sqrt{\left(x_{n_{PMU}}-x\right)^2+\left(y_{n_{PMU}}-y\right)^2} \end{aligned} \tag{5}$$

Where v is velocity, $\tau_{n_{PMU}}$ time difference of a wave front touching PMU and PMU that origin is placed. $x_{n_{PMU}}$, $y_{n_{PMU}}$ and $z_{n_{PMU}}$ are coordinates of PMU location and x, y and z are coordinates of disturbance.

For this method the time delay detection is very important and its bed detection influences on an estimation of location. The error of few percent can move the estimated location on the opposite side.

5 Test system

The algorithms for estimating the location of generator trip are tested on real power system ENTSO-E [6] with real Wide Area Measurement Systems (WAMS) data shared by ELPROS d.o.o [7]. The placements of PMUs are: Ljubljana, Bucharest, Dortmund, Almelo, Magdeburg and Stuttgart and are pointed in red colour.

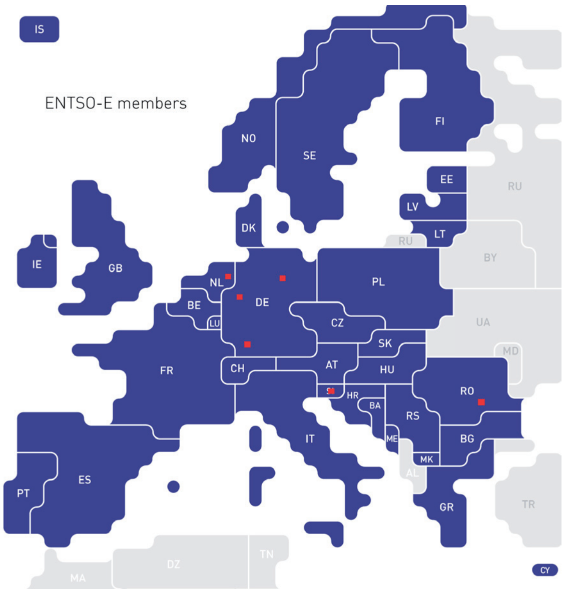

Fig. 1 ENTSO-E member countries with placement of PMU (red dote) [6].

6 Results

The massive blackout occurred on March 31 2015 in most of Turkey, just few days before a long-term agreement for a permanent connection between ENTSO-E and Turkey is signed [6]. In spite of this, these two systems were connected with synchronous alternate current (AC) lines and operated synchronously at the time of disturbance. The PMUs from Fig. 1 recorded oscillations of frequency shown on Fig. 2. As it is seen from Fig. 2 the oscillations have the biggest amplitude for PMU placed in Bucharest. For that reason the results of FFT analysis for frequency are demonstrated for this particular PMU.

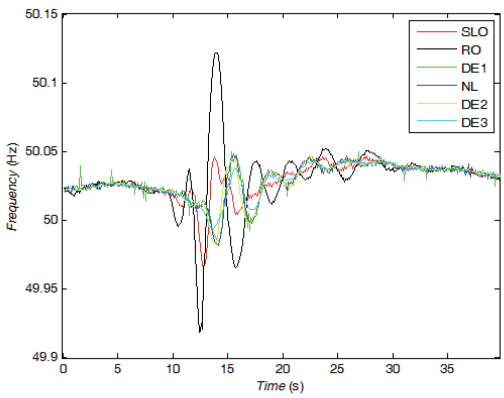

Fig. 2 Frequency oscillations recorded by PMUs in Europe during blackout in Turkey.

To estimate the location of disturbance the FFT of frequency was carried out (Fig. 3) and disturbance was detected (Fig. 4) due to fact that the maximum amplitude exceeded standard value for more than three times.

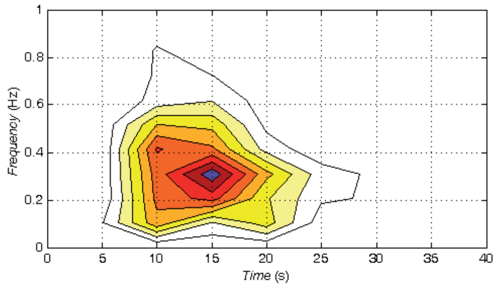

Fig. 3 FFT analysis of oscillations for PMU in Bucharest.

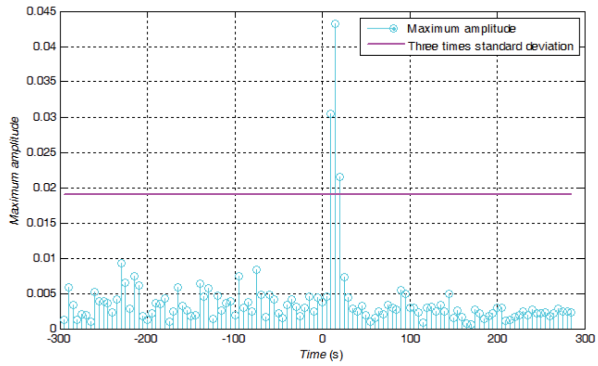

Fig. 4 Maximum amplitude of oscillations obtained by FFT analysis of frequency for PMU in Bucharest.

As the disturbance was detected, the next step was time delay and time difference detection. In this case the cross-correlation is used. The base signal is the frequency from PMU in Bucharest. The time difference between Bucharest and other PMUs are listed in Table 1.

Table 1 Time difference

PMU	Time (s)
Ljubljana	0.28
Dortmund	1.56
Almelo	1.54
Magdeburg	1.32
Stuttgart	1.54

As time differences are determined, the location of generator trip is estimated by both methods, gradient search method and multilateration.

Figure 5 presents the result for estimation of location of generator unit trip. With red colour the PMUs are marked and with black the real location is marked. The location of generator trip obtained by gradient search method is coloured blue and for multilateration the result is marked with purple. The result

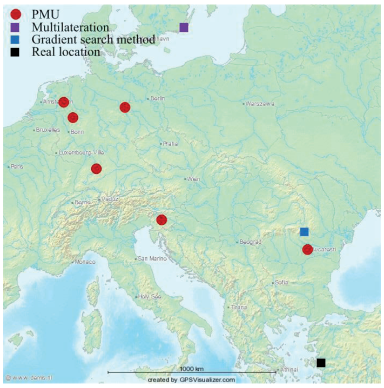

Fig. 5 Estimated location of generator trip.

for gradient search method is quite near from the real location, because this method only minimizes the function of distances. The result obtained by multilateration is far away from the real location, on the north. Such error is consequence that the multilateration is very sensitive method and that the geographic distance is not equal to the electromagnetic distance and that the velocity of electromechanical waves is not equal in all directions.

5 Conclusion

The proposed methods can help to estimate the location of generator unit trip, but the data must be very accurate.

The gradient search method does not always converge due to fact that the minimum of the function cannot be found because the geographic distance is not equal to the electromagnetic distance and the velocity is not equal in all directions.

The method of multilateration is not useful in all cases because the calculation is very sensitive and very high accuracy of data is required. Also in this case the geographic distance is not equal to the electromagnetic distance and the velocity is not equal in all directions. In some cases the time difference or delay needed to estimate the accurate location does not have enough digits. If the number of reference points is more than 5, it becomes an over-determined system and the estimated location is not always accurate or differs if only few points are used.

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